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SIXTH RAREFIED GAS DYNAMICS

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DIFFUSIVE SEPARATION IN FREE JETS OF
NITROGEN AND HELIUM MIXTURES

by

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DIFFUSIVE SEPARATION IN FREE JETS OF NITROGEN AND HELIUM MIXTURES

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ABSTRACT

Measurements of relative species concentration, jet structure, and N_2 rotational temperature using an electron beam are presented for free jets of nitrogen-helium mixtures. The results are compared with the predictions of the method of characteristics for the temperature distribution and with Sherman's nearly continuum theory for diffusive separation.

INTRODUCTION

The effects of diffusive separation in free expansions of binary gas mixtures from a sonic orifice into a low-pressure region has received considerable attention in recent years. A number of investigators have detected separation using sampling probes and skimmers,¹⁻⁵ and Rothe⁶ has studied a free jet expansion of argon and helium using an electron beam. Zigan and Sherman^{7,8} have developed a theoretical continuum model for diffusive separation of gas mixtures in free jets and a comparison is offered between this theory and the data presented in this paper. Predictions of the jet structure and temperature distribution using the method of characteristics⁹⁻¹¹ are also used as an approximate model with an effective specific heat ratio (γ) assumed constant throughout the flow field. The gases selected were nitrogen and helium because of their excellent emission characteristics when excited by an electron beam, their large difference in molecular weight, their different specific heat ratios, and because rotational temperature of the heavier particles could be measured. The techniques using the electron beam in mixtures of N_2 and He have been described in a previous paper¹² where the exhaust from a supersonic nozzle was investigated. The uncertainties reported in that article led to the present study.

SIXTH RAREFIED GAS DYNAMICS

RESULTS AND DISCUSSION

The method used in this experiment consisted of surveying the flow field of the free jets of a gaseous mixture of $n_{\text{He}}/n_{\text{N}_2} = 2$ (n = number density) with an electron beam to measure the species concentration variations and, therefore, the extent of diffusive separation. The N_2 rotational temperature distributions down the jet center line were also measured along with the jet physical dimensions using a flow visualization technique. A series of square-edged orifices and a convergent sonic nozzle were used to vary the Reynolds number and orifice diameter. Figure 1 shows a sketch of the main features of the apparatus and of a free jet flow field issuing from a sonic orifice. The nozzle used in this experiment had an 11° convergent portion and a 3.17-mm-diameter throat that was 10 mm in length. The square-edged orifices consisted of circular holes drilled in a 1.53-mm-thick plate.

Species concentrations.— Measured ratios of helium atoms to nitrogen molecules along the jet center line as a function of x/d for various orifices and the convergent sonic nozzle are shown in figure 2. Reynolds number was thus systematically varied by both changes in orifice diameter and stagnation pressure. These measurements were made by comparing the electron beam excited 5016 \AA He line with the P branch of the 4278 \AA band of N_2^+ as described in reference 12.

The maximum values of nitrogen enrichment observed for the convergent nozzle and each of the square-edged orifices are shown in figure 3 as a function of inverse Reynolds number along with the maximum separation predicted by Sherman's theory. The experimental points were taken at the minimum values of $n_{\text{He}}/n_{\text{N}_2}$ shown in figure 2 and the theoretical curve is based on an x/d of infinity since this gives the maximum predicted separation. In applying the theory, the γ was assumed to be a constant (1.545) throughout, and the parameter of E time C from reference 8 was evaluated at 2.24.

The jet produced by the 3.17-mm-diameter convergent nozzle was studied in some detail so that lines of equal concentration ratio could be contoured and the results are shown in figure 4. The first conclusion to be drawn from

SIXTH RAREFIED GAS DYNAMICS

these data is that the separation of gas species in a free jet of an N_2 - He mixture does not completely agree with Sherman's theory nor with the experimental results of Rothe for a mixture of monatomic gases. This is readily seen from the results shown in figures 2, 3, and 4. The degree of separation appears to be a function of nozzle geometry as well as of Reynolds number. In all the jets measured, the heavier gas is enriched first at a short distance from the exit and along the center line, then this trend is reversed and the helium concentration is found to be greater in all other parts of the flow field. The lack of agreement between the data and the near continuum theory is not only illustrated by the fact that the separation is generally greater than predicted (see fig. 3) but that it first reaches a maximum and then decreases with a decrease in Reynolds number.

The contours shown in figure 4 would seem to violate the principle of species conservation but one must consider two factors which could account for this distribution. First, the density gradients in a free jet are such that a large number of the gas particles are concentrated in a small volume near the jet exit where the N_2 enrichment is a maximum, and the much larger volume where He enrichment is found is a region of relatively small particle concentration. The helium-enriched internal shock of the jet has a relatively greater density than the region both inside and outside the jet at values of x/d greater than one-half, so that normal diffusion would tend to increase the helium concentration both inside and outside the jet boundary, as seen in figure 4.

Second, some separation process other than that proposed by Sherman may influence free jets of N_2 - He mixtures. Since the jet passes rapidly from a collision-dominated region near the orifice to a virtually collision-free region farther downstream, it is possible that the difference in the light and heavy particle velocities along the streamlines in this vicinity could give rise to a relative enrichment of nitrogen in the transition region.

Rotational temperatures.- For insight into the probable species parameters along the center line of the jet, N_2 rotational temperatures were measured using both pure N_2 and

SIXTH RAREFIED GAS DYNAMICS

the mixture of N_2 - He. Some typical results are shown in figure 5 and tend to verify the assumption that in the mixtures the different particles have different temperatures and therefore different velocities as they pass into the nearly collision-free region of the jet. This conclusion is drawn from the fact that the nitrogen rotational temperatures (T_R) for the mixture are consistently above the expected distribution for continuum flow at x/d 's greater than one-half (x is distance downstream from the orifice and the d is geometric orifice or throat diameter). The predicted temperature distribution was calculated by the method of characteristics for x/d 's greater than 1 for the γ 's of the pure gases and for the mixture ($\gamma = 1.545$). At the lower values of x/d the temperature distributions (dashed lines) were based on the measured values of T_R in the pure N_2 jet, and the sonic conditions computed at $x/d = 0$ for the γ 's shown in figure 5. This procedure was followed due to the uncertainty of the method of characteristics at low values of x/d (ref. 11). These measurements are somewhat limited as a method of analysis, since the rotational energy begins freezing at an x/d above 2 (for this $P_0 d$) as indicated by the veering-off of the measured values from the predicted distribution. Despite this limitation and the difficulties in determining T_R at low temperatures,^{13,14,15,16} figure 5 shows that at low values of x/d the T_R measurements effectively indicate the N_2 translational temperature.

Jet boundaries. - The results of the electron-beam flow visualization experiment are shown in figure 6 where the measured ratio of the maximum radius of the jet internal shock to the exit radius is plotted against pressure ratio for pure N_2 , pure He, and for the mixture. Results for the mixture are shown for two different Reynolds numbers (based on nozzle throat conditions). These measurements are compared with the predicted distributions using the method of characteristics for various γ 's based on the measured concentrations. The conclusion drawn from this figure is that the method of characteristics solutions cannot be used to predict accurately the free jet boundaries for a gaseous mixture whose constituents vary in γ when diffusive separation takes place. The lower Reynolds number data appear to be in agreement with the predictions based on the γ for the maximum measured N_2 concentration ($\gamma = 1.528$) but the higher Reynolds number data show poor agreement with this

SIXTH RAREFIED GAS DYNAMICS

γ , that of the initial composition ($\gamma = 1.545$) and that of the maximum measured helium concentration ($\gamma = 1.588$). In any case, there is little justification for selecting a constant γ if gradients in γ exist both axially and radially in the jet due to variations in the concentration.

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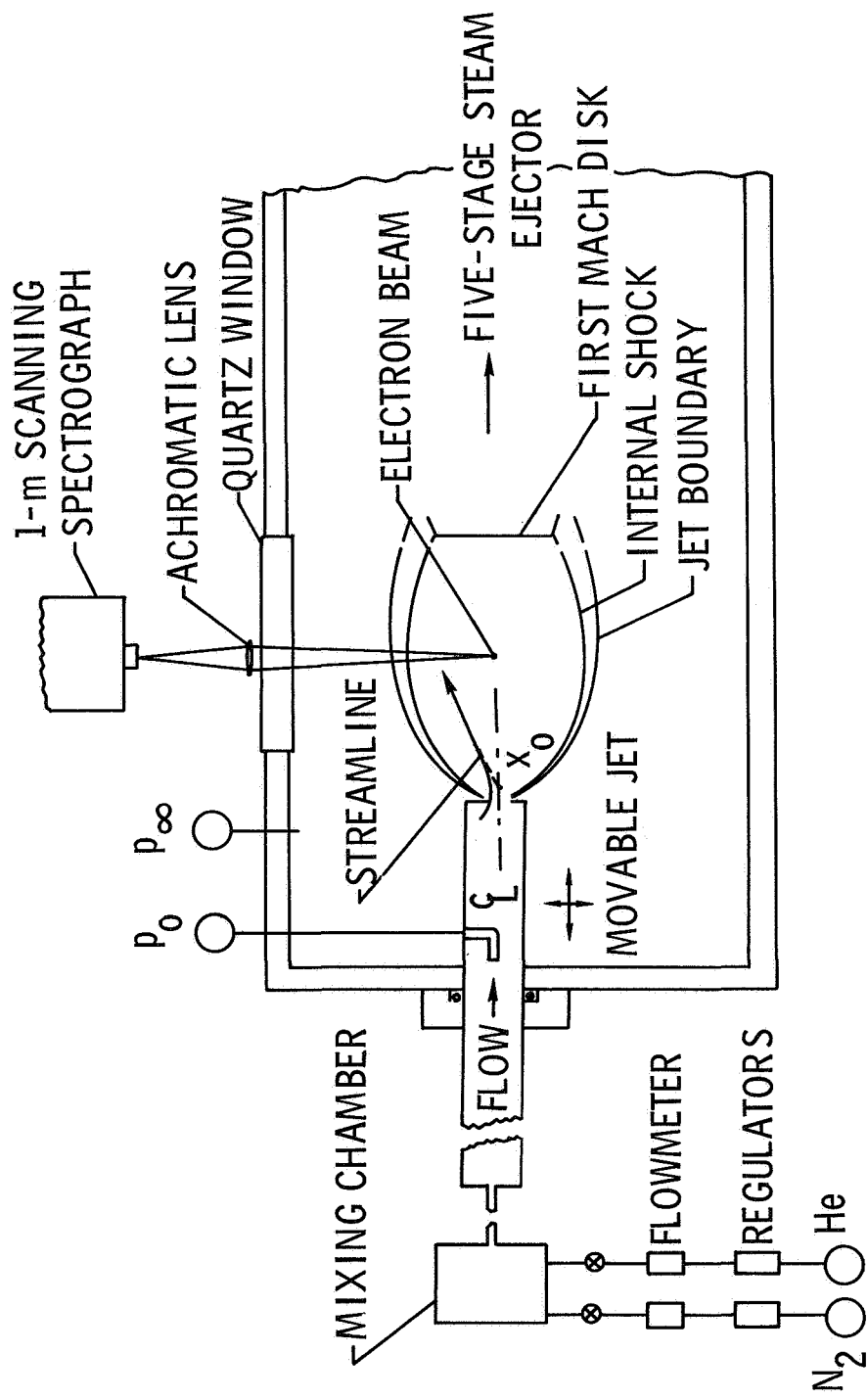


Figure 1.- Schematic of setup and flow field.

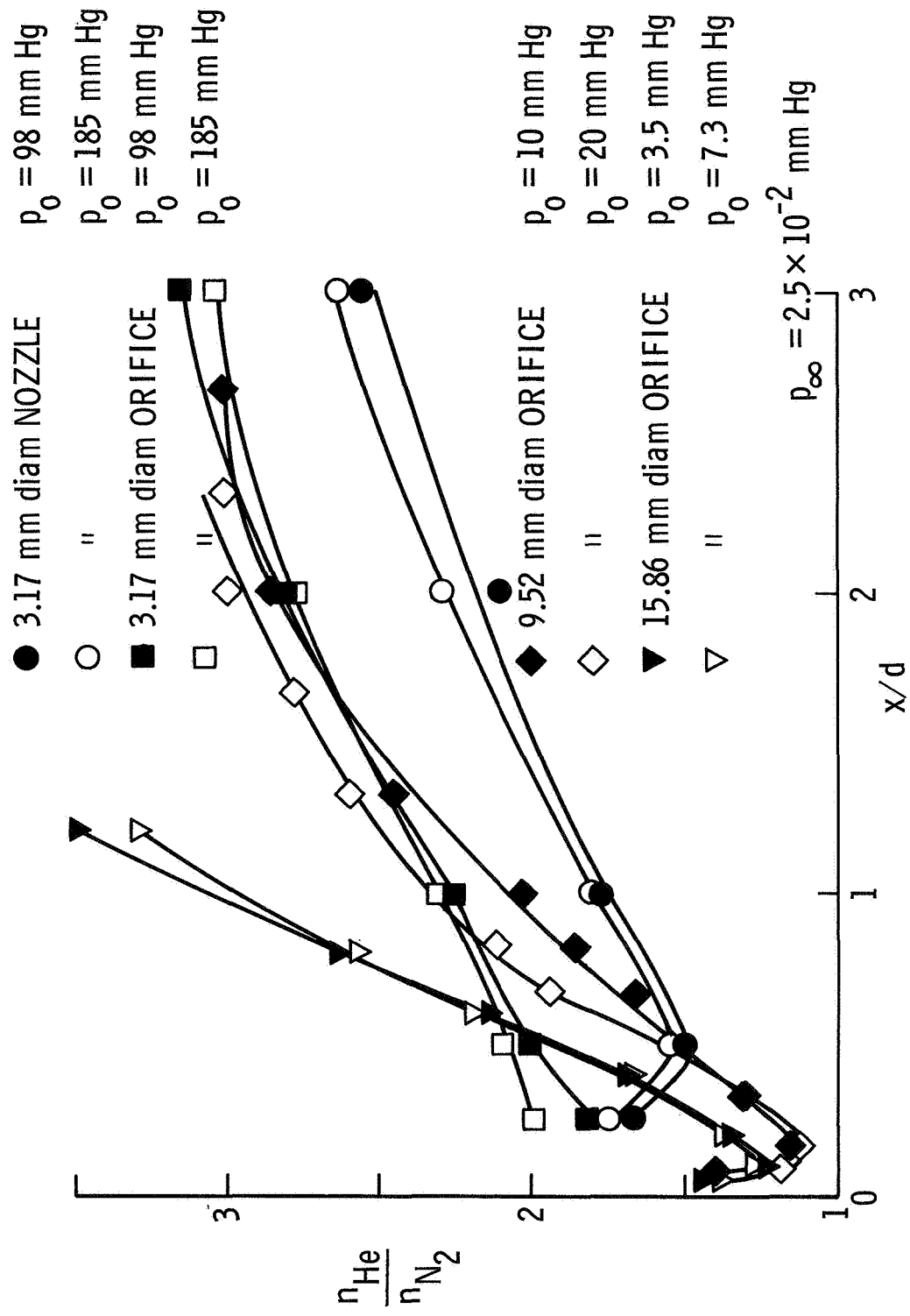


Figure 2.- Measured $\frac{n_{\text{He}}}{n_{\text{N}_2}}$ along center line, $\left(\frac{n_{\text{He}}}{n_{\text{N}_2}}\right)_0 = 2$, $Re_0 = 700$ to 7440 .

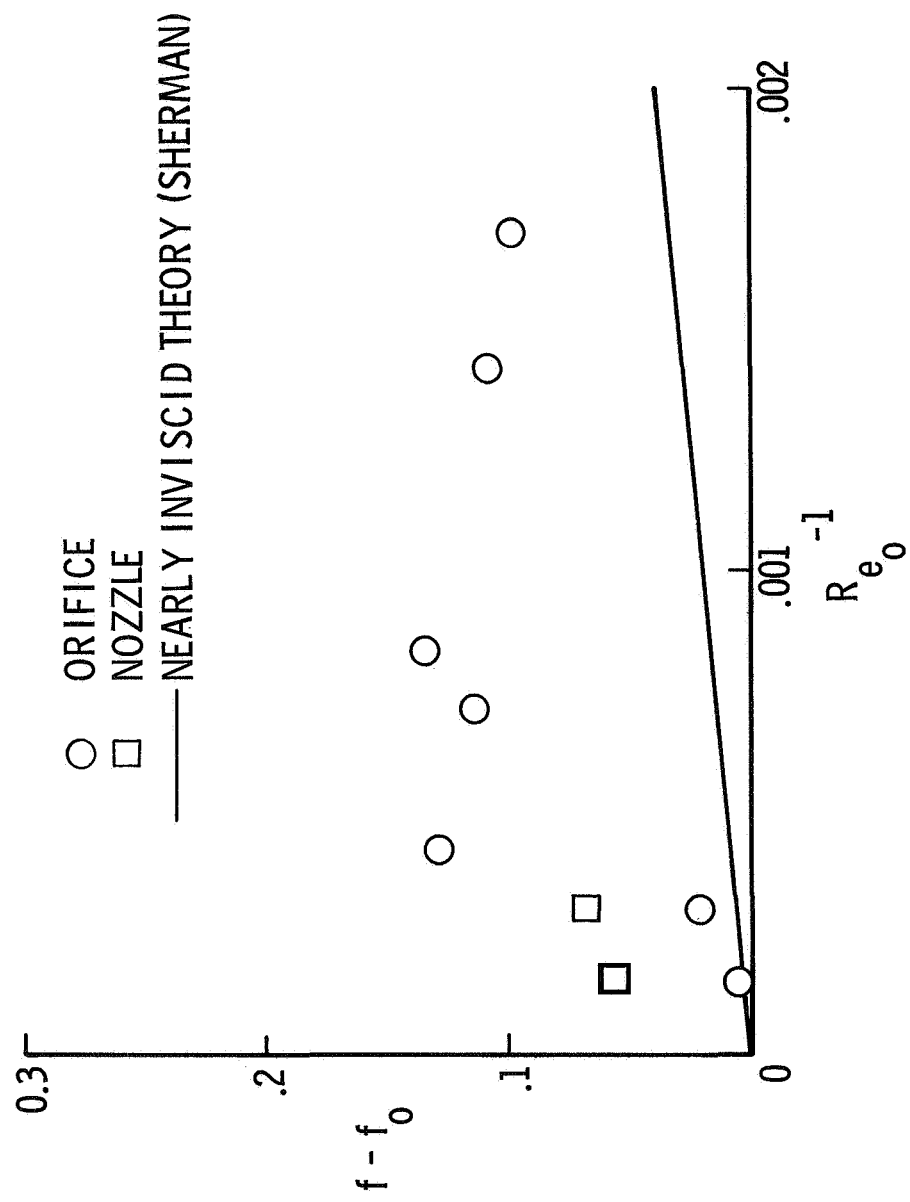


Figure 3.- Measured values of separation and Sherman's theory versus Re_0^{-1} .

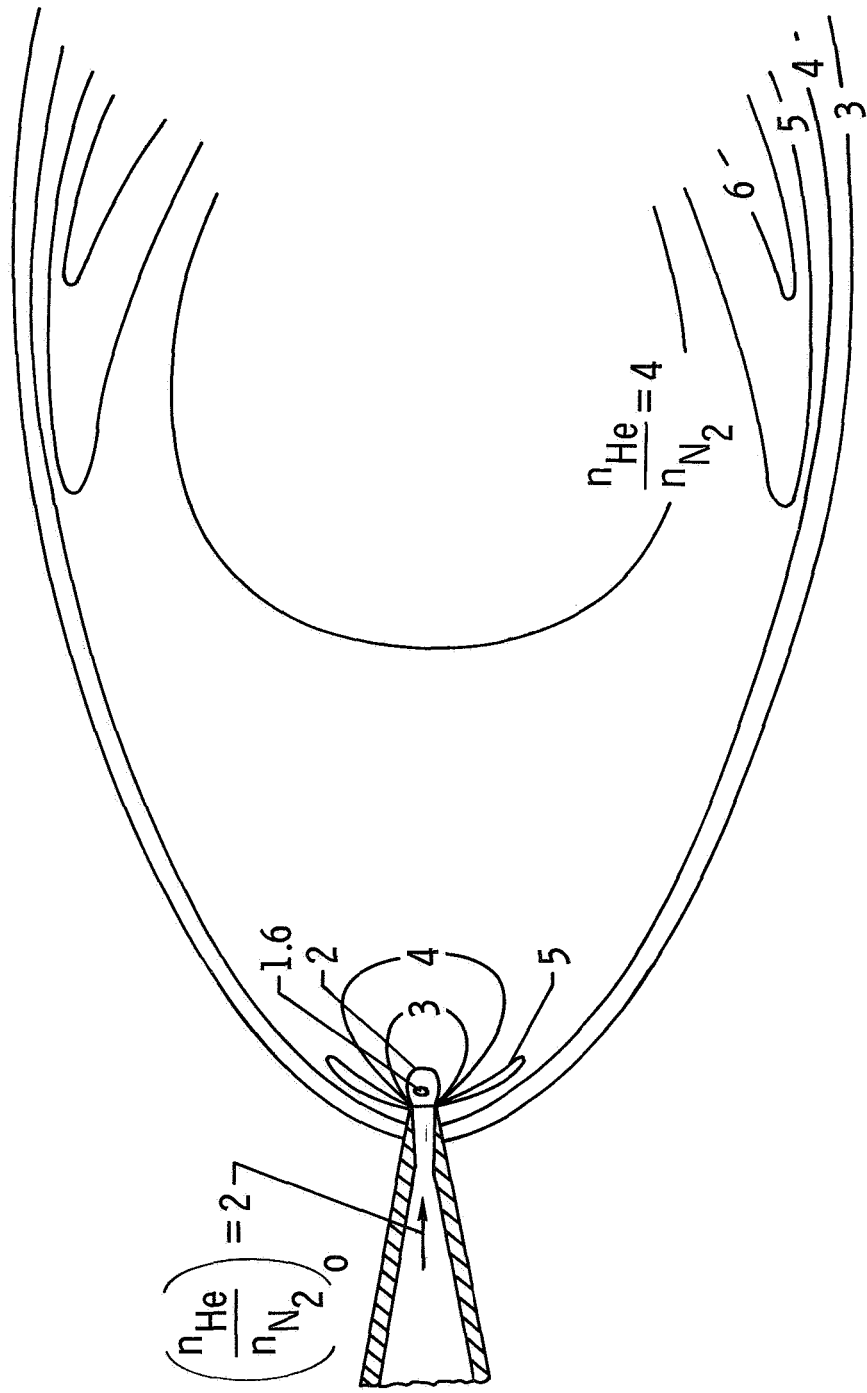


Figure 4.- Lines of equal concentration for sonic nozzle, $p_0 = 153 \text{ mm Hg}$, $p_\infty = 2.5 \times 10^{-2} \text{ mm Hg}$, $R_{e_0} = 6150$.

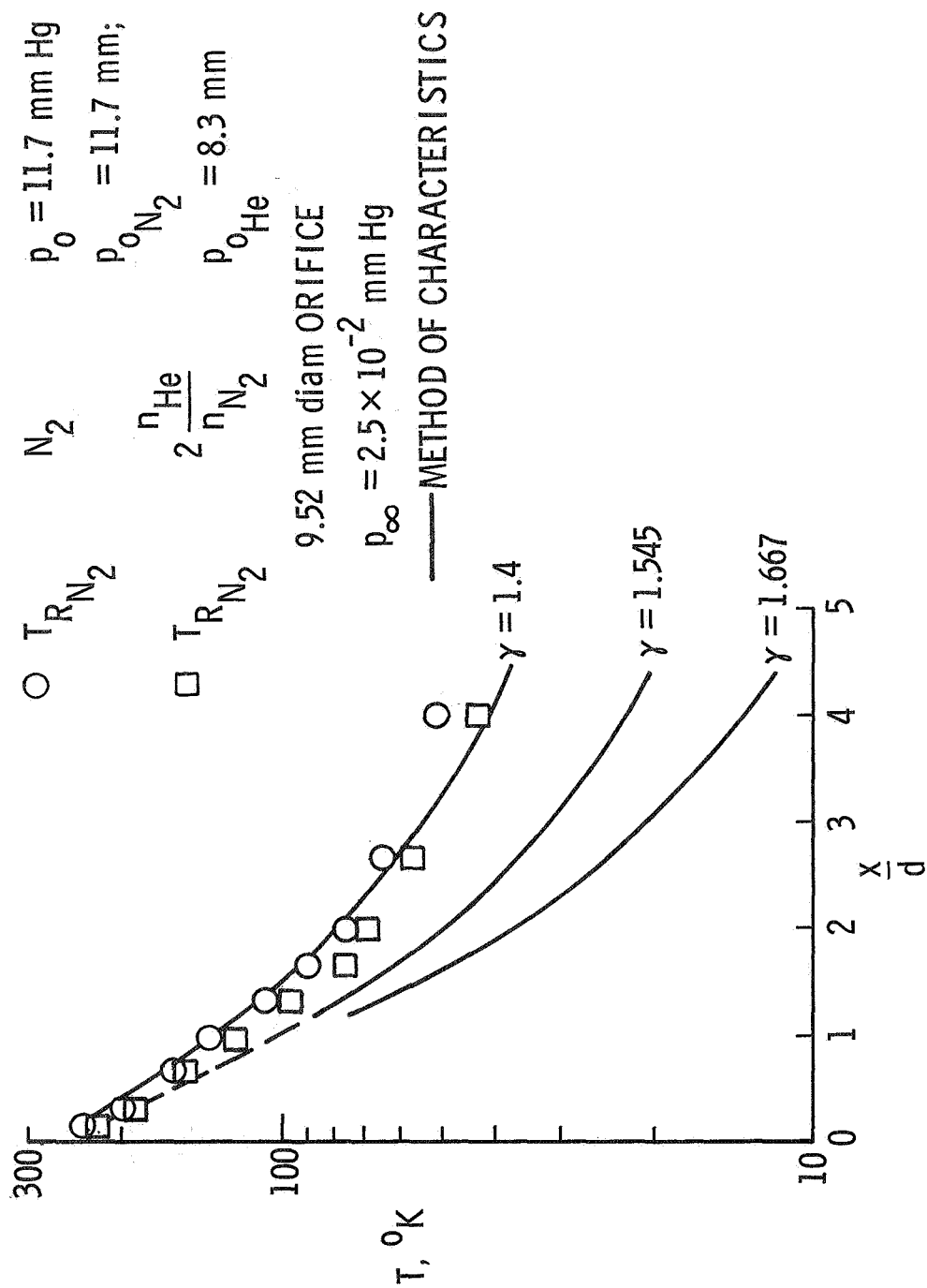


Figure 5.- Measured $T_{R_{N_2}}$'s in N_2 and mixture and predicted temperatures.

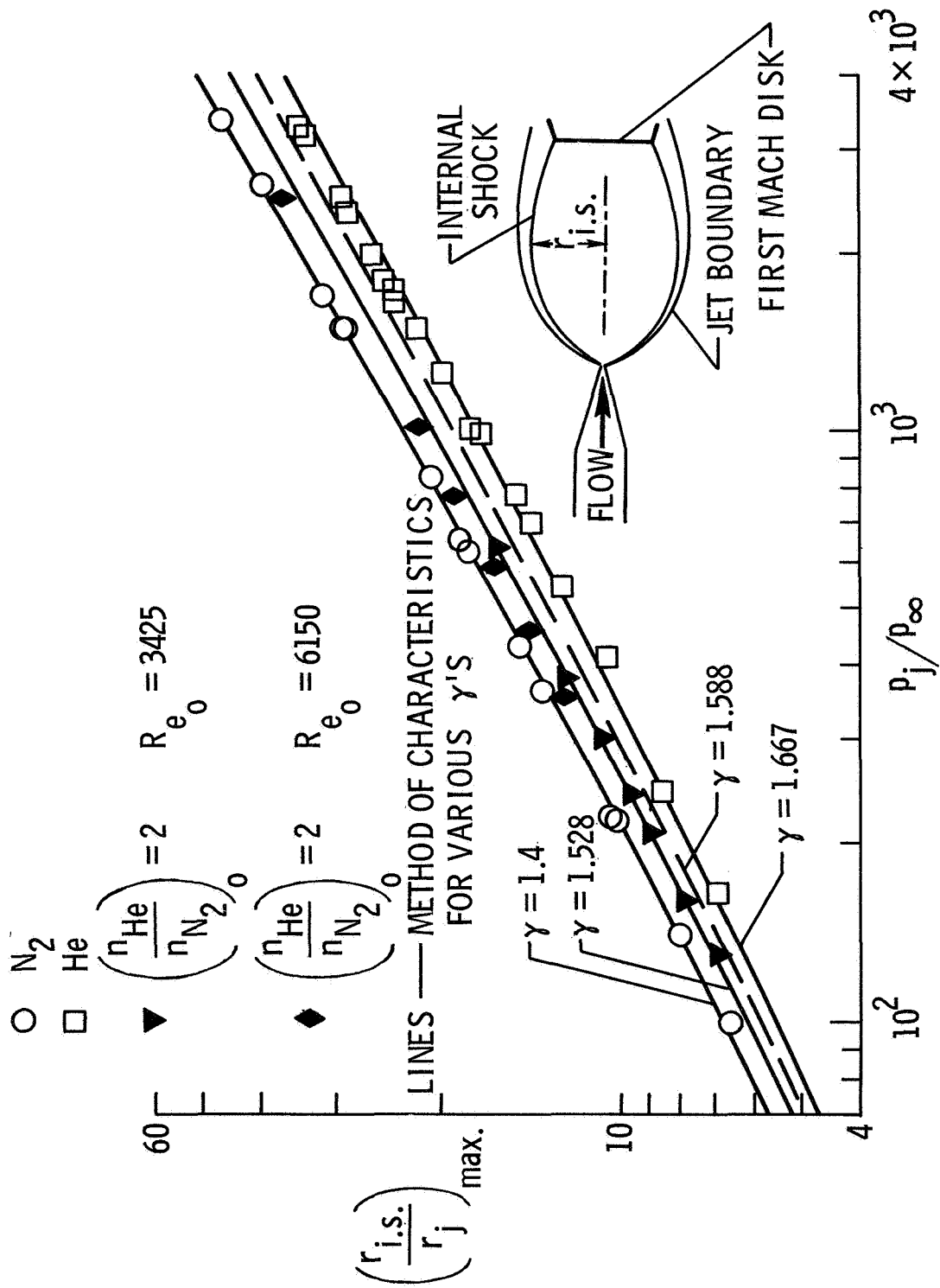


Figure 6.- Measured and predicted maximum jet radius versus pressure ratio for sonic nozzle.